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Survey of Beaver-related Restoration Practices in Rangeland Streams of the Western USA

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Abstract Poor condition of many streams and concerns about future droughts in the arid and semi-arid western USA have motivated novel restoration strategies aimed at accelerating recovery and increasing water resources. Translocation of beavers into formerly occupied habitats, restoration activities encouraging beaver recolonization, and instream structures mimicking the effects of beaver dams are restoration alternatives that have recently gained popularity because of their potential socioeconomic and ecological benefits. However, beaver dams and dam-like structures also harbor a history of social conflict. Hence, we identified a need to assess the use of beaver-related restoration projects in western rangelands to increase awareness and accountability, and identify gaps in scientific knowledge. We inventoried 97 projects implemented by 32 organizations, most in the last 10 years. We found that beaver-related stream restoration projects undertaken mostly involved the relocation of nuisance beavers. The most common goal was to store water, either with beaver dams or artificial structures. Beavers were often moved without regard to genetics, disease, or potential conflicts with nearby landowners. Few projects included post-implementation monitoring or planned for longer term issues, such as what happens when beavers abandon a site or when beaver dams or structures breach. Human dimensions were rarely considered and water rights and other issues were mostly unresolved or addressed through ad-hoc agreements. We conclude that the practice and implementation of beaver-related restoration has outpaced research on its efficacy and best practices. Further scientific research is necessary, especially research that informs the establishment of clear guidelines for best practices.

Keywords Beaver dam analog · *Castor canadensis* · Check-dam · Incised stream · Water · Wildlife

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Introduction

North American beaver (*Castor canadensis*) are ecosystem engineers that provide many ecosystem services, especially in arid and semi-arid regions where water is a limited resource (Pollock et al. 1995). In western North America, these particularly arid regions are dominated by shrublands, grasslands, and dry forest types that are used for livestock production, and hence called rangelands. In western rangelands, beaver dams can create a series of impoundments in streams that stretch for kilometers in otherwise dry landscapes, dramatically altering streamside and floodplain vegetation (Cook and Zack 2008). They may also increase surface and subsurface storage and groundwater elevations that contribute to channel complexity and residence times (Majerova et al. 2015; Bouwes et al. 2016), factors that could lead to stronger flow permanence in channels subject to seasonal drying. As such, beavers and beaver dams in rangelands can provide increased availability of water, food, cover, and other features that support species that live in aquatic and riparian habitats (Gibson and Olden 2014), as well as upland species that transiently depend on these ecosystems (e.g., Greater sage-grouse, *Centrocercus urophasianus*; Donnelly et al. 2016). Increased availability of water and productivity of riparian vegetation can also support human uses in arid regions, such as irrigation and livestock production, provided the latter are managed appropriately (Hough-Snee et al. 2013; Swanson et al. 2015). Beaver dams also provide crucial regulating ecosystem services (e.g., altered hydrology and streambed aggradation), supporting services (e.g., nutrient storage and cycling), and cultural services (e.g., spiritual and recreational opportunities) in arid landscapes. The importance of these ecosystem services will likely increase in the coming years as issues of carbon storage (Wohl 2013), water availability (Hood and Bayley 2008), and wildlife habitat (Donnelly et al. 2016) are heightened under warming climates, loss of snow, changes in runoff, and increased likelihood of extended droughts (Beechie et al. 2012; Williams et al. 2015; Ault et al. 2016).

The ecosystem services provided by beavers in western rangelands were likely diminished from the region during the intensive fur-bearer trapping period of the 19th century. Local extirpation of beaver populations was followed by large-scale changes in agrarian land-use practices with the arrival of European settlers (Novak 1987; Obbard et al. 1987), which left remaining beaver populations disjunct until beaver restoration efforts in the early to mid-20th century. The combined loss of beavers and changes in land and water use left many streams vulnerable to incision and degradation, although the exact causes of incision of western streams are debated (see Supplemental Information, as well as Naiman et al. 1988; Belsky et al. 1999; Polvi and Wohl 2013). Historically, beaver dams likely minimized or reversed stream channelization and incision processes by slowing water flow, trapping sediments and organic matter, raising water tables, and creating multiple channels within the same stream (Polvi and Wohl 2013; Gibson and Olden 2014). Today, beaver populations are well established throughout their historical range (Müller-Schwarze 2011) including many rangeland streams (Gibson and Olden 2014). The apparent benefit of beavers to the hydrology and ecology of rangeland streams (Miller et al. 2012; Beschta et al. 2013) has motivated beaver-related stream restoration (McKinstry and Anderson 1999).

Translocation of beavers, or the intentional movement of beavers into formerly occupied habitats, and installation of instream structures that mimic the effects of beaver dams have been used sporadically as stream restoration strategies for decades (Pollock et al. 2015). Other strategies such as changes in land-use practices to allow for recovery, or planting vegetation in riparian areas, have led to natural recolonization by beavers, who then build dams and contribute to the restoration process (Beschta et al. 2013; Swanson et al. 2015). The relative success or failure of these strategies is often assessed on a site-by-site basis, if at all, and lessons learned from these projects are often not shared outside of local government offices or privately owned operations (but see Pollock et al. 2014). Although researchers are beginning to rigorously examine beaver-related restoration of rangeland streams in the western USA (e.g., Bouwes et al. 2016), there are still no peer-reviewed studies that assess what types of beaver-related stream restoration practices are being implemented or considered, and what can be learned from their successes and failures.

To address this need, the goals of this study are to inventory restoration projects that include beaver translocation or instream structures that mimic the effects of beaver dams on public and private rangelands in the western USA, and to better document such practices, identify information gaps, and promote the exchange of information for more effective restoration. We address two questions: (1) How and where are translocated beavers or structures that mimic beaver dam effects being used to restore degraded rangeland streams?; and (2) What information is available about these projects that might improve the effectiveness of future restoration projects? We draw on our findings to discuss some of the social, ecological, hydrological, and legal/regulatory issues that beaver-related restoration approaches raise to provide insight and perspective for future stream restoration actions in western rangelands. Throughout the paper, we refer to beaver translocation as intentional movement of beavers into formerly occupied habitats; we do not cover the topic of introducing beavers outside of their historical range.

Methods

To address our research questions, we conducted an inventory of projects involving the translocation of beavers or the installation of instream structures that mimic beaver dam effects (hereafter artificial structures). We developed a template for systematic data collection about each project (see Figure S.1). The template was designed to record: (1) information about the nature of the project; (2) its purpose, time frame, and location; (3) the landowners and partners involved; (4) the current and historical occurrence of beavers in the project area; (5) sources of financial support; and (6) project accomplishments and challenges. We completed a template for each project through a combination of web searches, literature and document review, and email and telephone inquiries.

We searched scientific literature (i.e., refereed journals) and documents (i.e., non-refereed reports and articles) published 1950–2016 for records of beaver-related restoration projects. Literature searches were performed with Google Scholar using the search terms “incised streams”, “beaver”, “beaver dam analog,” and “artificial beaver dam.” We focused on primary research performed in the arid or semi-arid regions of the western USA.

We conducted email and telephone inquiries October 2015–December 2016 to obtain information about unpublished projects completed 1950–2016. To conduct inquiries with key participants, we developed a list of initial contacts by identifying known beaver researchers, people working on beaver-related restoration projects, or organizations having an interest in stream or watershed restoration. We then used chain-referral sampling to identify additional contacts (Bernard 2011), and ceased sampling at saturation, when the same projects were mentioned repeatedly, and no new projects surfaced. If the people on our list of contacts did not respond after two attempts by email and two by phone, we did not include them in the study. We explained to participants that the goal of our effort was to determine the extent to which beaver translocation and artificial beaver dam-like structures were being used as tools to restore incised streams or otherwise improve rangeland streams. These direct inquiries resulted in a purposive sample of wildlife and fisheries biologists, restoration ecologists, hydrological specialists, and others from federal and state agencies and non-governmental organizations or working groups that work with beavers or stream restoration in the western USA. Our contact list included 75 organizations that work on stream restoration in California, Colorado, Idaho, Montana, Nevada, Oregon, Utah, Washington, and Wyoming. Of these, we spoke or corresponded via email with individuals from 59 of the 75 organizations (79%), and 32 of 59 (54%) shared information to help us complete the project templates (Tables S.1 and S.2). In some cases multiple contacts were working on the same projects; in these cases only one contact submitted information. In other cases contacts submitted information for more than one project, sometimes in multiple states.

We obtained information for 97 projects undertaken between 1950 and 2016 that had been completed or were in the process of being implemented at the time of data collection (Table S.3). Of these projects, 7 were identified from research articles that focused on beaver translocations or artificial structures as restoration tools, and the remaining 90 were compiled from information provided by the agencies and organizations contacted. Although it is unlikely that we gathered information on all projects that were conducted during this time period, our sample is large enough to enable characterization of beaver-related restoration practices over the last few decades. We mapped the geographic distribution of projects using ArcGIS 10.3.1 (ESRI, Redmond, CA). Specific coordinates for the locations of released beavers were not included in the geodatabase and georeferenced points were offset slightly from the precise location of the projects to protect the sites.

Results

How and Where are Translocated Beavers or Structures that Mimic Beaver Dam Effects Being Used to Restore Degraded Rangeland Streams?

Of the 97 projects identified, 76 used beaver translocation, 14 used artificial structures that mimic beaver dam effects in some form, and 7 used both artificial structures and beaver translocation (Table 1). Projects were scattered throughout western rangelands, although we found a concentration of projects in central Idaho, and only one in Nevada (Fig. 1). Projects tended to be driven by partnerships of diverse stakeholders, including government agencies and private organizations or citizens. Twenty-four of the projects were conducted on private lands and 13 involved mixed ownership of both private and public, but none of these projects were conducted without involvement of state, tribal, or federal partners. Stream restoration projects involving

Table 1 Stream restoration projects in our sample involving beaver translocation, artificial structures, or where artificial structures were placed prior to beaver translocation or recolonization

State	Number of projects			
	Beaver translocation	Artificial structures	Both	Total projects
California	0	3	0	3
Colorado	1	0	0	1
Idaho	51	1	5	57
Montana	2	2	0	4
Nevada	0	1	0	1
Oregon	5	2	1	8
Utah	3	0	0	3
Washington	12	2	0	14
Wyoming	2	3	1	6
Total	76	14	7	97

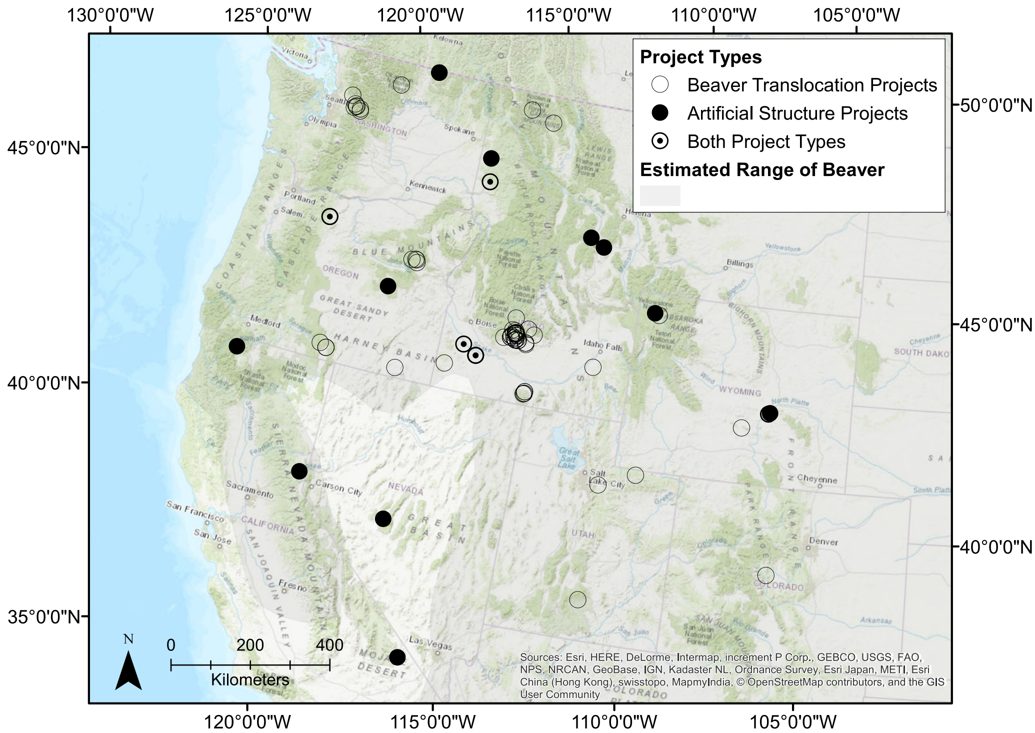

Fig. 1 Approximate locations of 97 restoration projects involving beaver translocation (open circles), artificial structures (filled circles), or structure installation prior to beaver translocation or recolonization (i.e., both; bullseye) implemented 1950–2016 in western rangelands. The estimated range of North American beaver is shown in shaded gray (source: Natureserve 2017)

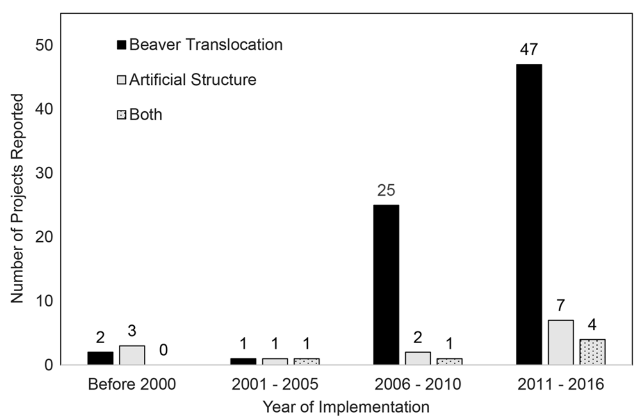

Fig. 2 The number of projects reported relative to their first year of implementation for projects involving beaver translocation, artificial structures, or artificial structures that were installed prior to beaver translocation or recolonization (i.e., both). The year of implementation was unknown for three projects (1 beaver translocation, 1 artificial structure, 1 both)

beaver translocation appear to have increased considerably since the year 2005 (Fig. 2). In comparison, the number of projects using artificial structures is increasing more slowly. The goals of the projects in our sample were fairly diverse and varied slightly between beaver translocation and artificial structure projects (Table 2). The need to relocate nuisance beavers was the most common goal of beaver translocation projects, followed by water storage. Water storage was also listed as the most common goal of artificial structures. Riparian vegetation restoration, sediment control, and fish and wildlife habitat improvement were also listed as goals of artificial structure projects (Table 2).

Table 2 The number of projects in our sample ($n = 97$ projects) that were implemented under a variety of goals subdivided into those involving beaver translocation, those involving artificial structures, or where artificial structures were placed prior to the translocation or recolonization of beavers ("both"). The project goals are organized from most common to least common

Project goals	Number of projects			
	Beaver translocation	Artificial structure	Both	Total Projects
Nuisance Beaver Relocation	48	0	0	48
Water Storage	15	8	5	28
Riparian Vegetation Restoration	6	6	0	12
Sediment control	6	4	1	11
Unspecified	8	2	0	10
Fish and Wildlife Habitat Improvement	1	4	2	7
Cultural	1	0	0	1

Several projects listed more than one objective and thus columns do not add to 97 projects

Table 3 Terms used by participants during email or phone conversations to describe artificial structures that were installed with the general concept of mimicking some of the effects of beaver dams

Term	Description
Adjustable standpipe to block water	A standpipe installed into a culvert to raise the level of the water intake and increase the level of the pond behind the culvert
Artificial beaver dam	A low-profile dam constructed of rock and gravel with the intention that water breaches the dam at high flow
Beaver dam analog	Posts installed across a stream intended to trap material, often interwoven with wood or other organic material to aid in the process
Check dam	Low-profile dam constructed of rock
Insta-dams: shredded tree material	Shredded tree material of varying sizes placed across the main flow of a stream
Low-profile dam	A dam constructed of rock, wood, or other materials, usually with the height set at bank-full depth
Plug and pond structure	Rock and gravel pushed into stream channels to block water flow and create ponds
Post-assisted woody structure	Posts driven into the streambed with smaller woody material woven between them
Reinforcement of old beaver dam	Posts, canvas, plastic, or other materials used to reinforce an existing beaver dam
Rock and wood structure	Weirs and makeshift dams constructed of rock and wood
Sheet piling sill	Sheets of metal installed across a stream

Where artificial structures were installed, we found that materials and designs varied considerably, as did terminology referring to them (Table 3). We found that structures were generally made of either rock or wood, and all were designed to be semi-porous to water, sediment, and aquatic organisms and low enough to overtop during high flow. Most artificial structures were installed in sequence or series, similar to beaver dams, which enhanced their function. Low-profile dams made of piled rock were called check dams or artificial beaver dams, depending on the project. Low-profile dams constructed of woody material were called post-assisted woody structures or beaver dam analogs (i.e., BDAs). The term BDA was coined by Pollock et al. (2015) in the first edition of *The Beaver Restoration Guidebook: Working with Beaver to Restore Streams, Wetlands, and Floodplains* where they describe them as "channel-spanning structures that mimic or reinforce natural beaver dams" (p. 82). They are constructed by installing wooden posts into the streambed and either letting material accumulate passively or actively weaving material between the posts. Several projects fit this description, but use of this term has increased considerably in recent years.

What Information is Available About These Projects That Might Improve the Effectiveness of Future Restoration Projects?

Post-restoration monitoring was documented at only 22% of projects (21 of 97), but the information provided was insufficient to conduct an analysis of the determinants of project success or failure (Table 4). We expect more information will become available as young projects (implemented after 2011) continue to develop. We learned of only two projects with long-term monitoring plans.

Table 4 The number of projects in our sample ($n = 97$) where post-treatment monitoring was not documented and is thus unknown, where no monitoring occurred, and where some form of effectiveness monitoring was conducted over several years

Years of monitoring	Number of projects
Unknown	63
None	13
1	13
2–5	4
6–10	4

Case Studies of Beaver-Related Restoration Using Artificial Structures

We collected information on relatively few projects that used artificial structures to mimic the effects of beaver dams on streams or used a combination of artificial structures and beaver translocation ($n = 21$; Table 1). However, the examples that we found were well described, some were very large and involved many structures, and all provided insight into the potential and limitations of these restoration tools. Additional case studies can be found in Pollock et al. (2015).

In eastern Oregon, one private landowner installed 640 low-profile rock dams, coined "artificial beaver dams" or ABDs, starting in 2001 (Fig. 3a; Davee et al. 2017). These ABDs were built sequentially along incised streams using rock that was mined on site. The primary goal of these structures was to raise the water table to the point that the adjacent meadows (former terraces) could support grass and be grazed or hayed. The structures ultimately created or

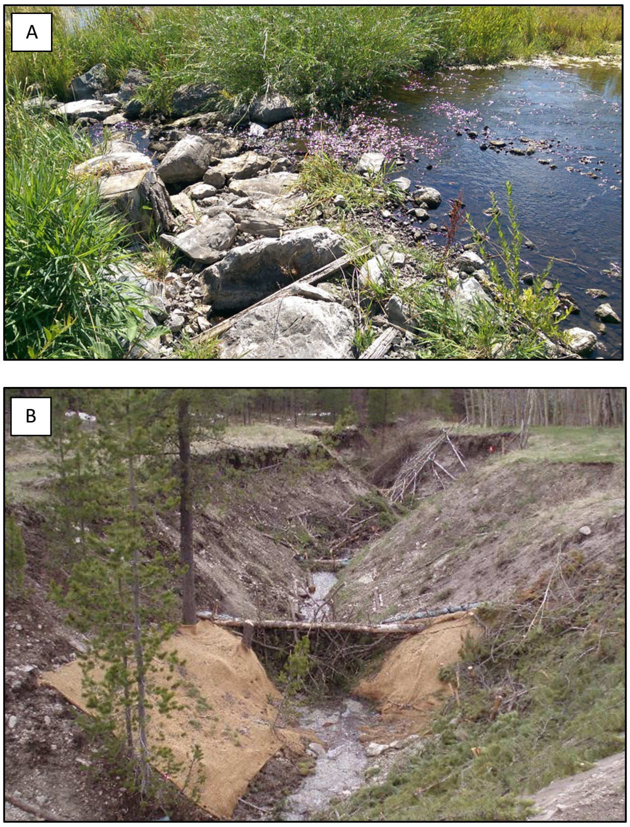

Fig. 3 Examples of two types of artificial structures (designed to mimic some of the effects of beaver dams) used in stream restoration projects. **a**) A rock structure dam installed by a private landowner in eastern Oregon and referred to as an "artificial beaver dam." **b**) A wood structure installed by a private organization in western Montana and referred to as a low-profile wooden dam

helped improve riparian habitat and maintained surface water into the dry summer, thus providing perennial water for fish, wildlife, and livestock. The height of each dam approximates bank-full depth of the unincised channel so that dams are readily overtopped during spring runoff. The landowner reported that the ABDs have created perennial streams and ponds where incised, temporary streams previously existed. He also reported that wet meadows now dominate riparian areas where sagebrush once grew. These sagebrush flats were probably created after the channels initially incised. To aid the reversal of this process, the landowner mechanically removed the sagebrush in some areas prior to inundation when the ABDs were installed. State and federal hydrologists and geomorphologists, with permission from the landowner, are conducting a watershed-scale water budget associated with the implementation of these structures. While the landowner is pleased with perceived ecological and economic outcomes so far, regulators have expressed concerns about the use of low-profile rock dams for stream restoration given their potential effects on fish (e.g., affecting fish passage). The

Fig. 4 Example of reinforced beaver dam in southwestern Idaho. Five beavers were translocated and released at this site, which resulted in a new dam built on top of the instream structure (inset) and additional dams built upstream of the release site

landowner has worked with state biologists to modify some of these structures to allow better fish passage, although the success of these modifications has yet to be evaluated (Davee et al. 2017).

In another project, 305 low-profile dams made of woody material (Fig. 3b) were installed along streams in southwestern Montana as part of an ongoing effort to reduce sediment flow in streams in the Mount Haggin Wildlife Management Area, which were strongly affected by the impacts of hydraulic mining. The first structures were installed in 2014 by state hydrologists with help from volunteers, and the project is ongoing. The core material in these structures is pine planks, which are intended to provide fish passage while increasing sediment deposition and aggradation (White et al. 2011; Pollock et al. 2015).

Artificial structures and beaver translocation were used successfully together at Stoneman Creek, a stream in southwestern Idaho (Fig. 4). This stream has been extensively studied because it contains a population of Columbia spotted frogs (*Rana luteiventris*, Munger and Lingo 2003). Local landowners reported that beavers were extirpated from Stoneman Creek around 1992, either by trapping or shooting. In the years that followed, the beaver dam on the creek eroded and local reaches of the stream incised more than a meter. Consequently, the wetland upstream of the dam drained and the abundance of spotted frogs declined (Munger and Lingo 2003). In 2001, the breach in the beaver dam was plugged with t-posts and plastic tarps to reinforce the old beaver dam (see Fig. 4), and five beavers were released at the site. The beavers improved the temporary artificial structure and built several more dams upstream from the release site. As beaver ponds formed upstream, frog abundance increased dramatically (Lingo 2013). The success of this beaver translocation may be attributed to the proximity of aspen and willow, a moderate stream gradient, and valley form (Lingo 2013).

Discussion

This inventory of beaver-related stream restoration practices in western rangelands has revealed four key findings around which we focus our discussion: (1) beaver-related restoration encompasses a broad range of practices for a broad range of goals; (2) better regulatory guidelines could facilitate beaver-related restoration; (3) restoration assessments will benefit from including social as well as ecological components; and (4) the practice and implementation of beaver-related restoration has outpaced research on its efficacy and best practices.

Beaver-Related Restoration Encompasses a Broad Range of Practices for a Broad Range of Goals

One of the central difficulties in assessing beaver-related restoration projects is the range and breadth of both restoration practices and desired restoration outcomes. Though there are often general goals of improved habitat or hydrologic conditions, there is rarely an explicit understanding of what improvement or success means from a social or ecological standpoint, and how it might be measured. We demonstrate here that resource managers and practitioners from many organizations and states are both interested in and implementing beaver-related restoration, but without clear guidance as to which practices are most appropriate for which goals. An emerging pattern is that restoration actions can be grouped as either directly involving beavers or not. The translocation of beavers was by far the most common practice, perhaps because of ease of implementation and cost (McKinstry and Anderson 1999). Restoration actions not involving beavers could be further subdivided by the primary materials used for dam construction, either rock or wood/plant material. Rock has the advantage of durability during high flows, whereas wood structures appear more "natural" and transient. However, the goals of these structures were often similar: slow water flow, increase aggradation, and improve both instream and riparian habitat (Gibson and Olden 2014; Pollock et al. 2014). Regardless, a lack of necessary decision-making tools for land owners and managers is limiting adoption of best practices given site-level and landscape-level conditions and desired outcomes. We are hopeful that the continued development of tools such as the Beaver Restoration Assessment Tool (BRAT; Macfarlane et al. 2014) will aid this process.

Better Regulatory Guidelines could Facilitate Beaver-Related Restoration

One suite of issues to address before implementing beaver translocation or beaver dam-mimicking devices has to do with conflicting and sometimes contradictory regulations surrounding stream restoration and beaver translocation. During the course of this study, we conversed with several organizations who work specifically to relocate nuisance beavers. In every case, practitioners expressed frustration at the complexity of laws and regulations regarding the handling and movement of beavers, which may be issued at the state, county, or municipal level. Additionally, many persons working in this field expressed concern about disclosing the location of their beaver translocation sites, because beaver harvesting on public lands in many areas is loosely regulated. Along with removing beavers from the landscape, ongoing beaver harvesting has been shown to alter behavior of surviving beavers, at times reducing ponded surface area produced through damming activities (Schulte and Müller-Schwarze 1999). Better definition and enforcement of laws regarding the handling and trapping of beavers are needed. In states such as California, where beaver translocation is illegal, assessment of the potential benefits of this restoration tool may be warranted.

Perhaps the urgency of stream restoration and the need to move nuisance beavers in many areas explains why the stringent precautions that are often taken with other species (e.g., to improve translocation success and prevent the co-introduction of parasites and disease) have not always been considered when translocating beavers. Suggested precautionary measures include a period of quarantine, clinical examination, fecal examination, blood testing, microbial culturing, and necropsy of individuals from source populations (Viggers et al. 1993). Although difficult to determine due to the large scale of translocation efforts that have already taken place (Jenkins and Busher 1979), there is some evidence that sub-species of North American beaver exist, or at least, existed prior to large-scale translocations (Warren and Hall 1939; Larson and Gunson 1983). Research focusing on the geographic ranges of sub-species would provide valuable information about which populations are most appropriate to source beavers for a specific destination, thereby improving the likelihood of successful re-establishment of beavers at the new site. Improved understanding and preservation of the evolutionary legacy of beavers in North America is warranted.

Legal and regulatory issues for artificial structures (e.g., artificial beaver dams or beaver dam analogs) abound as well. Multiple regulatory agencies operating at different jurisdictional scales may be involved, depending on the site, in review and permitting relating to the design, planning, and construction of structures. They include federal agencies (e.g., US Army Corps of Engineers and the US Fish and Wildlife Service), state agencies (e.g., state departments of fish and wildlife, and water), and county or city agencies. A greater understanding is needed of the benefits and costs associated with so-called “artificial beaver dams” (constructed of rock), and the differences between these structures and beaver dam analogues made from wood. This understanding could help regulatory agencies to become comfortable with the permitting process of different types of structures. Some regulators we spoke with expressed concern that “branding” projects as beaver-related may be inappropriate and influence perceptions of the wide variety of structures emerging in the world of watershed restoration. Some of these artificial structures might be thought of and regulated as more traditional man-made dams, which will likely require considerable, and possibly unwanted, oversight (e.g., engineered design, permitting, inspections). If existing laws, policies, and regulatory frameworks create burdensome and costly barriers to installing artificial structures, landowners may decide to forgo the permitting process, leading to illegal or unregulated restoration activities.

Restoration Assessments will Benefit From Including Social as well as Ecological Components

In addition to geomorphological and ecological conditions, social factors are important for managers to consider in site selection, particularly because of the checkered history of how beavers and dams are perceived. We know that translocated beavers will move from their release sites, sometimes tens of kilometers (McKinstry and Anderson 2002; Petro et al. 2015), including onto neighboring properties. These post-release dispersals and population dispersion through time set the stage for potential negative interactions between translocated animals and people (Müller-Schwarze 2011). One potential solution to this issue is proper planning (Baldwin 2013). In Idaho, for example, the Wood River Resource Conservation and Development Council selects potential translocation destinations (usually, but not always, on public land) at their annual meeting, and communicates these plans with local landowners before nuisance beavers are translocated to these sites. The Beaver Restoration Assessment Tool (Macfarlane et al. 2014) is facilitating this process by identifying both beaver habitat suitability and potential human-beaver conflicts. Potential points of conflict are identified as roads, culverts, and land ownerships and uses (Baldwin 2013). Combining these potential conflict models with assessments of local landowner perceptions and attitudes towards beavers may provide more comprehensive information for evaluating the success of restoration projects and informing future projects.

Social considerations are also important for artificial structures that are intended to mimic the effects of beaver dams. These structures have biophysical impacts that affect people and their land use activities in ways that may be both desirable and undesirable. For example, artificial structures may enhance a rancher’s resilience to drought by retaining water in stream systems later into the summer. However, they may also affect the timing of hydrologic flows and water availability to downstream users, invoking water rights concerns. Moreover, artificial structures may not restore incised streams. Given that other land use and management practices likely contribute to stream incision, artificial structures may need to be combined with changes in land use and management, such as grazing practices that heavily impact riparian areas during dry summer months. Research to evaluate the social conditions that promote the success of artificial structures and other beaver-related stream restoration projects in western rangelands is needed, as is the integration of social and biophysical considerations in selecting sites for such projects.

The Practice and Implementation of Beaver-Related Restoration has Outpaced Research on its Efficacy and Best Practices

Our review of beaver-related restoration projects indicates that beaver translocation and artificial structures that mimic the effects of beaver dams are widely and increasingly used, but with few guidelines and little effort to monitor restoration effectiveness or assess social or environmental consequences. Perennially-available water may benefit livestock, agriculture and wildlife, but it may also change the timing and rate of water delivery to downstream water users. Hence, there is a strong need for research to provide the science necessary for informed decisions about beaver-related restoration practices.

Although beaver translocation projects were by far the dominant type in our sample (see Table 1), the effectiveness of beaver translocations in achieving restoration goals was either low or uncertain. Some beaver translocations failed because beavers either moved or died. These factors are consistent with beaver translocation research studies in Wyoming (McKinstry and Anderson 2002) and Oregon (Petro et al. 2015) where initial post-release survival rates were 0.49 ± 0.06 and 0.47 ± 0.12, respectively. In both studies, predation was the leading cause of mortality. In Wyoming, beavers were depredated an average of 17 days post-release (McKinstry and Anderson 2002). In Oregon, 57% of predator-related mortality occurred within the first week post-release (Petro et al. 2015).

Whereas beaver translocations are often facilitated by a need to remove nuisance beavers from another site, we suspect that these translocated animals may behave differently than beavers with established dams because of post-release stress. Of 114 translocated beavers in Wyoming, 51% moved >10 km from their release sites (McKinstry and Anderson 2002). In rangeland systems, high dispersal may also be associated with suboptimal riparian habitat conditions (e.g., lack of preferred food, lack of dam and lodge building materials, and increased perceived risk; Collen and Gibson 2001). One organization contacted in our study thought that its beaver translocation might have failed because of insufficient food sources at the site. The translocated beavers were presumed to have left the site or died by the end of the first winter. Other groups also reported failed beaver translocations, though they were not able to identify why beavers left the sites or did not survive. To counter this problem, some projects installed artificial structures several years ahead of beaver translocations to improve habitat before live animals arrived. From our sample of projects, we conclude that there is a need for better pre-restoration planning (e.g., potential project or release sites) and post-restoration evaluation (i.e., beavers or otherwise).

We lack a full understanding of the potential effects of artificial structures on fish and wildlife, and their habitat. Although most artificial structures allow fish passage during high stream flows (Bouwes et al. 2016), the effects on fish populations during the dry season are unknown. At low flow, artificial structures are more likely to become barriers to movement, form isolated pools, and raise water temperatures (Magoulick and Kobza 2003). However, negative effects on fish populations may be fewer in arid and semi-arid streams where species evolved with intermittent hydrology and seasonally variable habitat conditions. Recent research suggests that increased surface water storage and enhanced surface water-groundwater connectivity associated with beaver dams and artificial structures may buffer diel summer temperature extremes at the reach scale (Weber et al. 2017), but other studies suggest the opposite (i.e., greater diel variability) and increasing water temperatures (Majerova et al. 2015). We suspect that artificial structures may also create conditions that allow invasive species to persist or spread, such as the invasive American bullfrog (*Lithobates catesbeianus*) (Gibson and Olden 2014).

Use of artificial structures to create perennial water sources in arid or semi-arid landscapes where streams have been ephemeral since beavers were originally extirpated may simultaneously have positive and negative impacts. Some wildlife species depend on fluctuations in seasonal water availability to signal life history events such as emergence from diapause or initiation of reproduction (Hershkovitz and Gasith 2013). Also, perennially-flowing streams may transport and propagate species in systems where they were previously limited by seasonal dryness, thus altering entire stream assemblages (Reich et al. 2010). Historical conditions of streams, as well as potential increased vulnerability due to management and land use in an area should be considered before altering the water holding or distribution patterns in any watershed. Most of the projects in our sample were implemented relatively recently, and therefore present the opportunity for continued monitoring and adaptive management in the future.

Further study of the consequences of beaver dams for stream temperature, hydrology, and water budgets in arid lands will help inform beaver-related stream restoration efforts (e.g., Feiner and Lowry 2015; Majerova et al. 2015; Macfarlane et al. 2017; Weber et al. 2017). We have highlighted at least one study in eastern Oregon that is attempting to quantify these relationships for artificial structures made of rock (Davee et al. 2017). Similar efforts are underway in the Bridge Creek drainage of eastern Oregon where beaver dam analogs have been installed (Bouwes et al. 2016; Weber et al. 2017). Analysis of aerial photographs and satellite imagery might also be useful for monitoring and evaluating some aspects of vegetation condition, incision, and water retention associated with beaver translocation, naturally-occurring beaver dams, and artificial structures through time. Although some of this research is underway (Hood and Bayley 2008; Andersen and Shafroth 2010; Butler 2012; Malison et al. 2014; Pearl et al. 2015; Huntington et al. 2016), regional information about the temporal dynamics of both beaver populations (i.e., rates of colonization, extirpation, dispersal) and beaver dams (i.e., actively maintained vs. inactive and not maintained; breached vs. intact) is still needed. Furthermore, an inventory of incised streams and degree of incision could help resource managers prioritize where beaver-related restoration may be most beneficial. Newer mapping technologies, such as LiDAR, may also change our understanding of stream incision and could be used to monitor rates of recovery following beaver-related restoration.

There is a need to better assess where different beaver-related restoration approaches are most suitable, both socially and ecologically. For example, where are low-profile rock structures most appropriate as opposed to wooden structures that are more likely to periodically fail in a similar manner to beaver dams? There is a need for better information regarding the effects and efficacy of different artificial structures that result in ponding in rangeland streams, especially streams that dry seasonally or periodically under natural historical conditions. Similarly, better understanding of the regulatory requirements, social impacts (such as on water use by downstream landowners and on agricultural production systems), social acceptability, and costs of different beaver-related restoration approaches will help in evaluating which approaches are more feasible from a social standpoint. Also needed is research on how to mitigate potential negative effects of beaver-related restoration approaches. Continued research into the positive and negative perceptions and impacts of beavers on public and private lands is called for, including work on mitigating negative perceptions. This research path could provide quantitative data on the performance of beaver-related restoration that is needed to streamline permitting on more than a case-by-case basis. Research may also reveal the importance of beaver-related restoration for climate change mitigation, such as increased surface water for livestock, especially during drought, or carbon sequestration (Wohl 2013). This information also may lead to better educational outreach about ways to live with (rather than relocate or kill) beavers, and mitigate potentially damaging behaviors of beavers and concerns surrounding water rights. Finally, research to identify how to create a more enabling legal and policy environment that examines beaver-related stream restoration projects from a scientific viewpoint, based on research and monitoring, could improve implementation (when appropriate) and success of these approaches.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests.

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